QED-driven absorption of high-intensity lasers

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Workshop on High Energy Density Physics with BELLA-i

CHALMERS
UNIVERSITY OF TECHNOLOGY

- How do QED processes affect the absorption of laser light by plasmas?
- When do those processes become significant and how do we study these plasmas?
- What experiments are possible now or in the near future?

Classically

light

laser pulse

matter

electrons

ions

Classically

light

laser pulse

electron
heating
(Brunel,
j x B, IB)

matter

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matter

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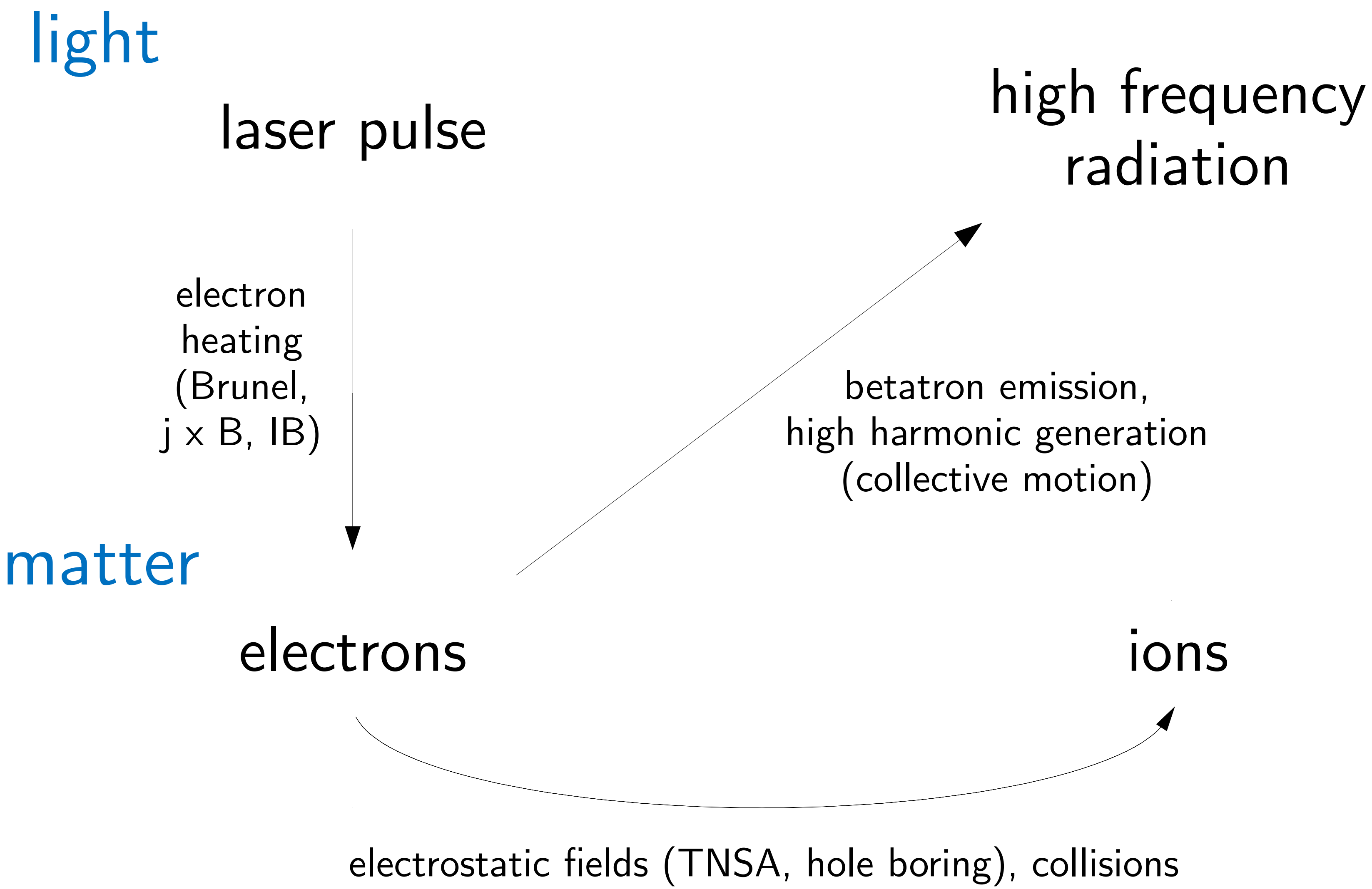
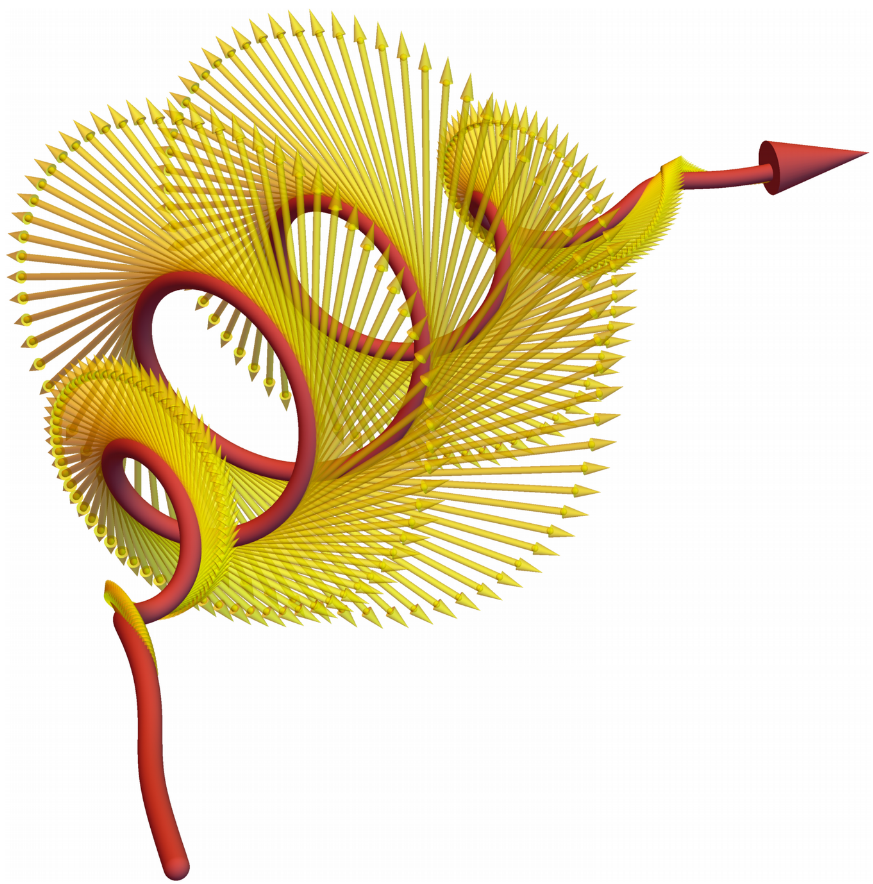
electrostatic fields (TNSA, hole boring), collisions

Absorption of laser light

Classically



Radiation from accelerating electrons



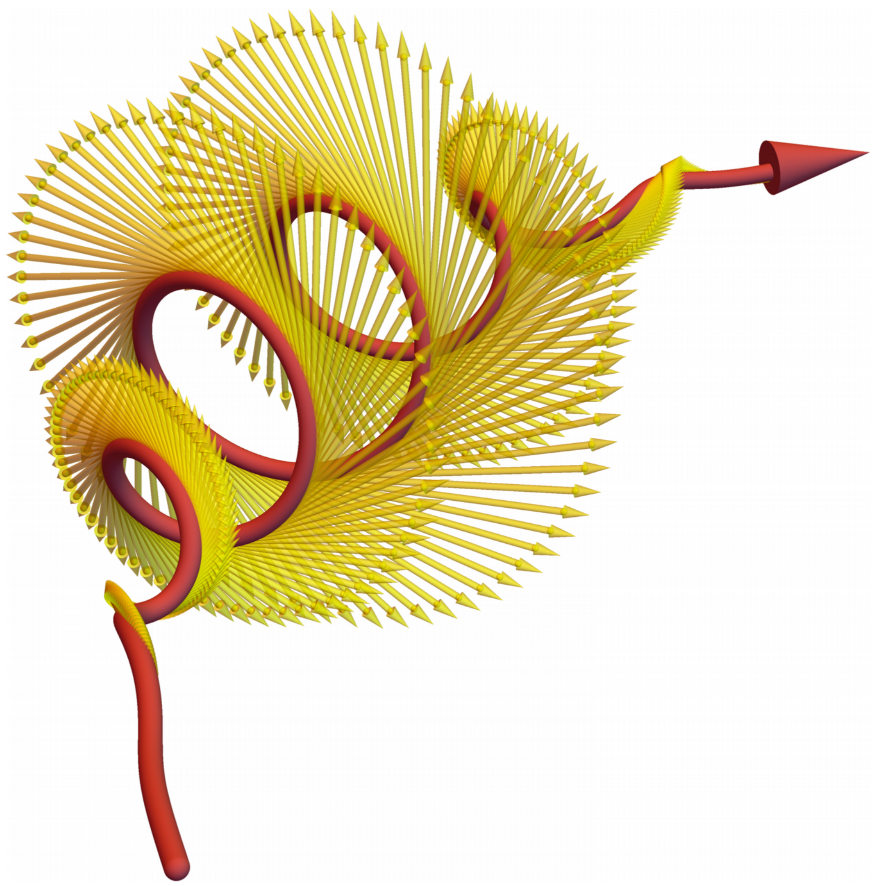
- Fractional energy loss to radiation in one laser period is

$$\frac{P_{\mathrm{rad}}\tau_{\mathrm{L}}}{\gamma mc^2} = 0.1\left(\frac{I}{2\times10^{22}\ \mathrm{Wcm}^{-2}}\right)^{3/2}$$

- i.e. 10% at the current intensity frontier.

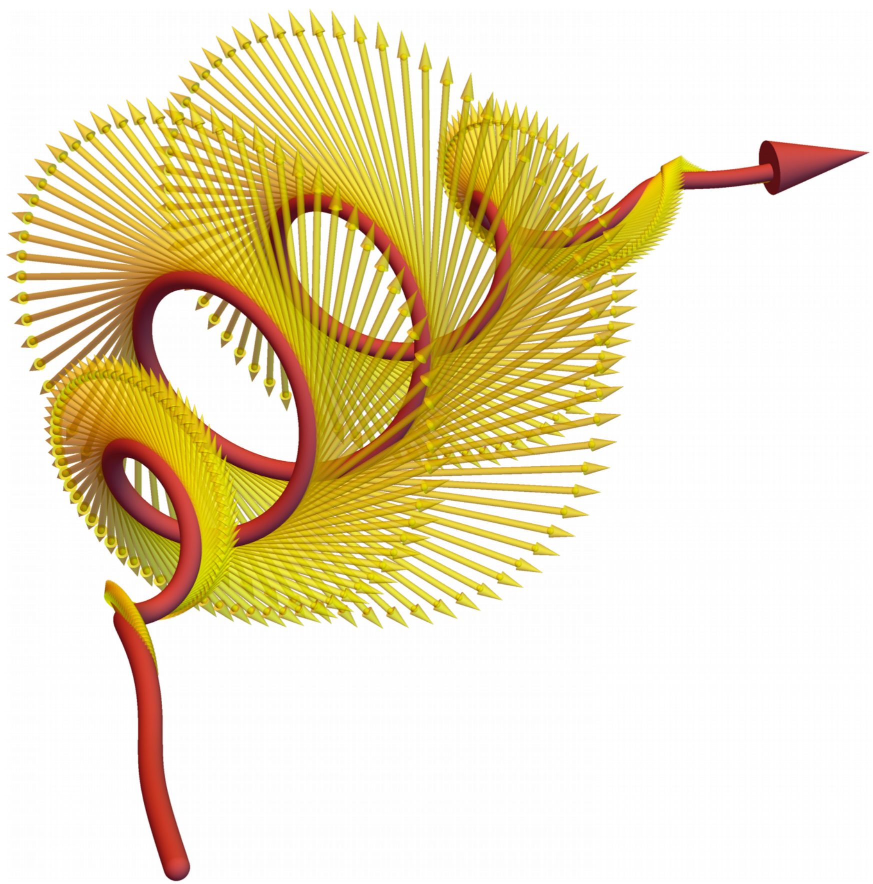
New absorption mechanisms

Radiation reaction



- Radiation carries momentum as well as energy, so the electron must recoil.
- The Lorentz force does not account for that recoil.
- Modify electron equation of motion.

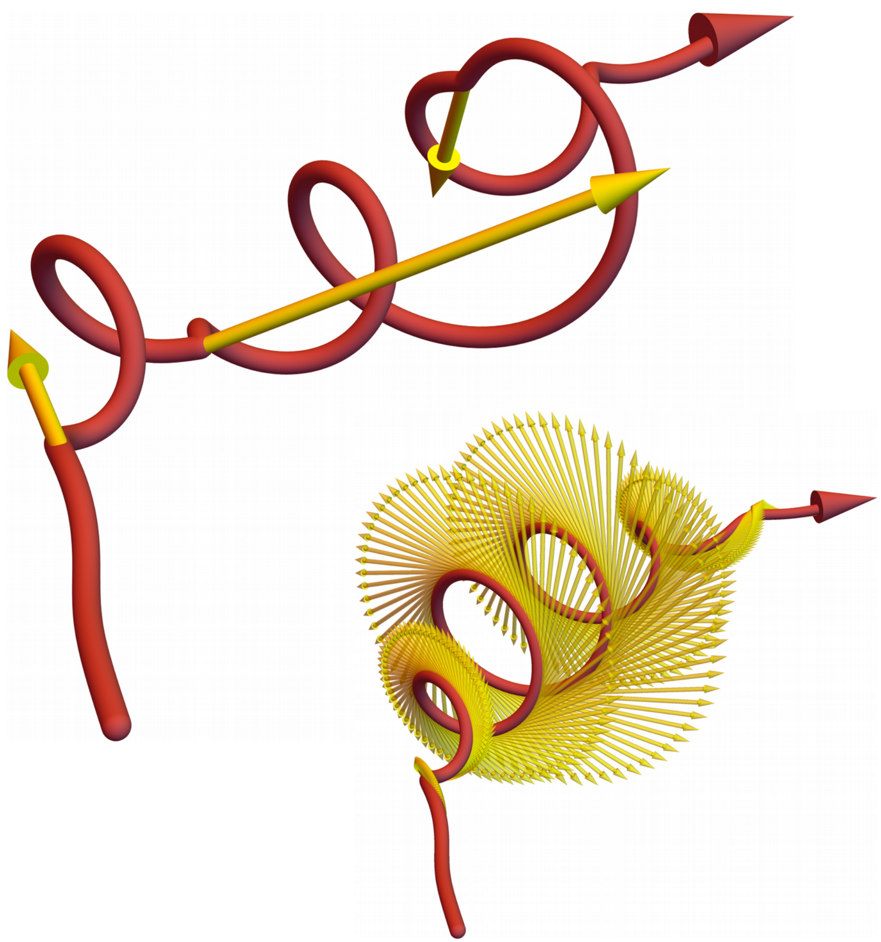
From classical to quantum radiation reaction



- Many different formulations of the classical radiation reaction force[1].
- Lorentz-Abraham-Dirac and Landau-Lifshitz are the most widely accepted.
- Can be derived[2] from QED, and are consistent to first order in α.

[1]Burton and Noble, Contemp. Phys. 55 2 (2014); [2]Ilderton and Torgrimsson, Phys. Lett. B 725 4 (2013)

From classical to quantum radiation reaction

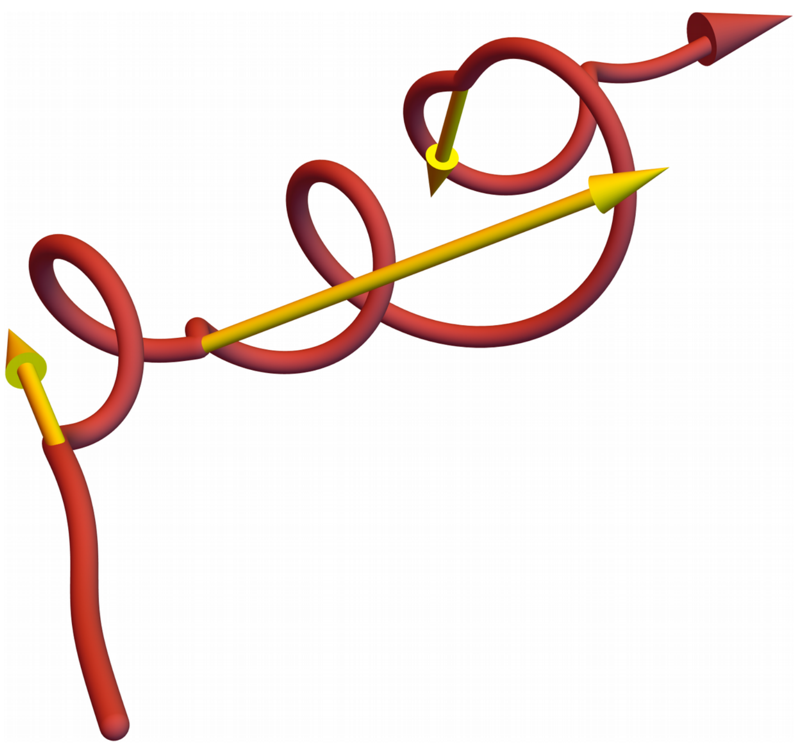


- When does a classical treatment of radiation become insufficient?
- Important parameter is χ (ratio of electric field in electron rest frame to the Schwinger field)

$$\chi = \frac{\gamma\,|\mathbf{E} + \mathbf{v} \times \mathbf{B}|}{E_{\mathrm{Sch}}}$$

New absorption mechanisms

Gamma ray emission

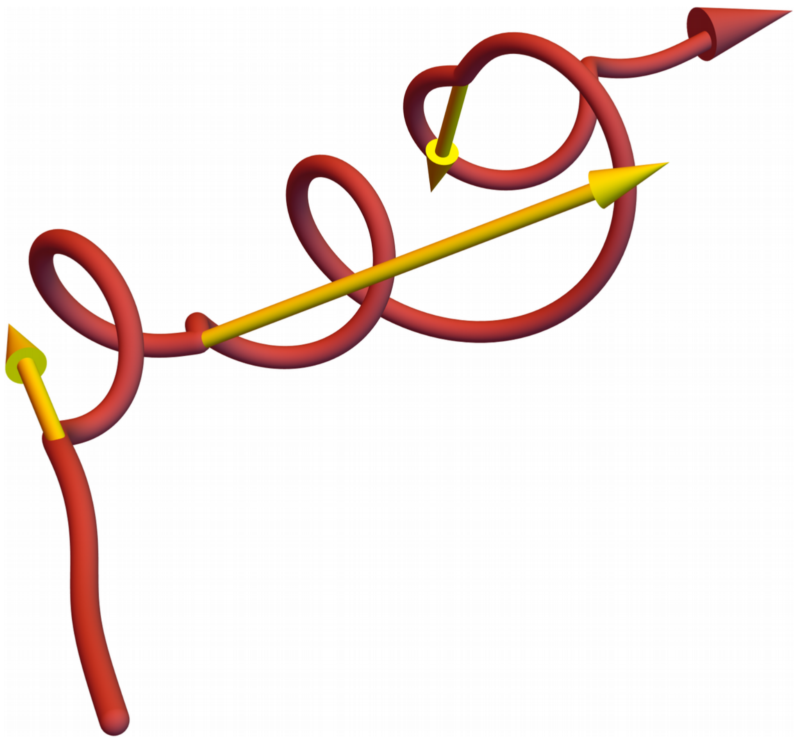


- A electron in a laser field has Lorentz factor about a_0
- So in a typical laser-plasma interaction

$$\chi = \frac{I\lambda}{5.7 \times 10^{23}\ \mathrm{Wcm}^{-2}\mu\mathrm{m}}$$

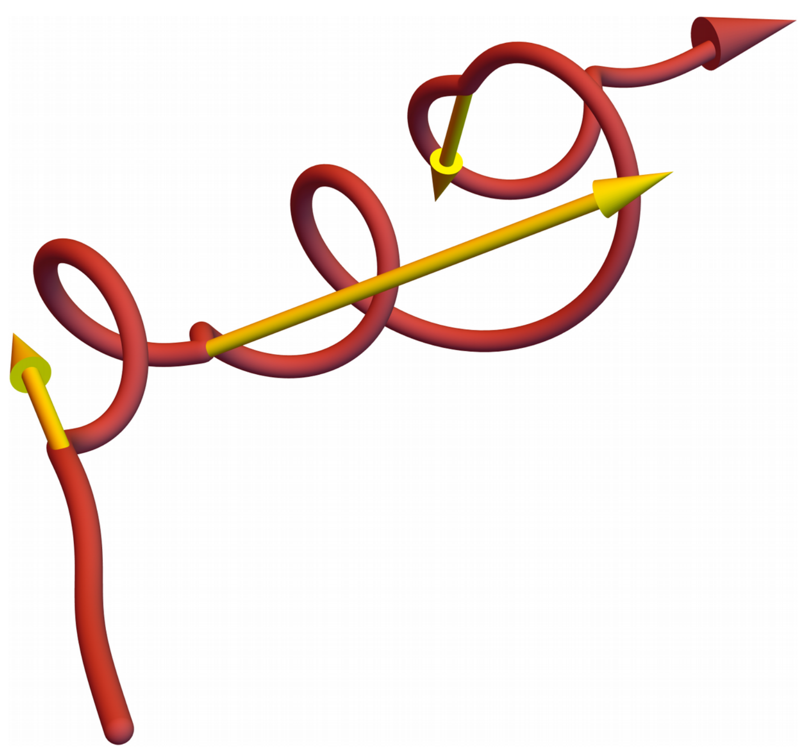
New absorption mechanisms

Gamma ray emission



- The typical photon energy as a fraction of the electron energy is 0.44χ.
- Electrons can lose a substantial fraction of their energy in a single emission.
- Emission becomes a **stochastic** process.

Gamma ray emission



- But even for $\chi = 0.1$, quantum corrections to the photon spectrum mean that a classical treatment overestimates the radiated power by 30%.

- The classical force must be damped by a factor $g(\chi) < 1$.

With gamma ray emission

light

laser pulse

high frequency radiation

electron heating (Brunel, j x B, IB)

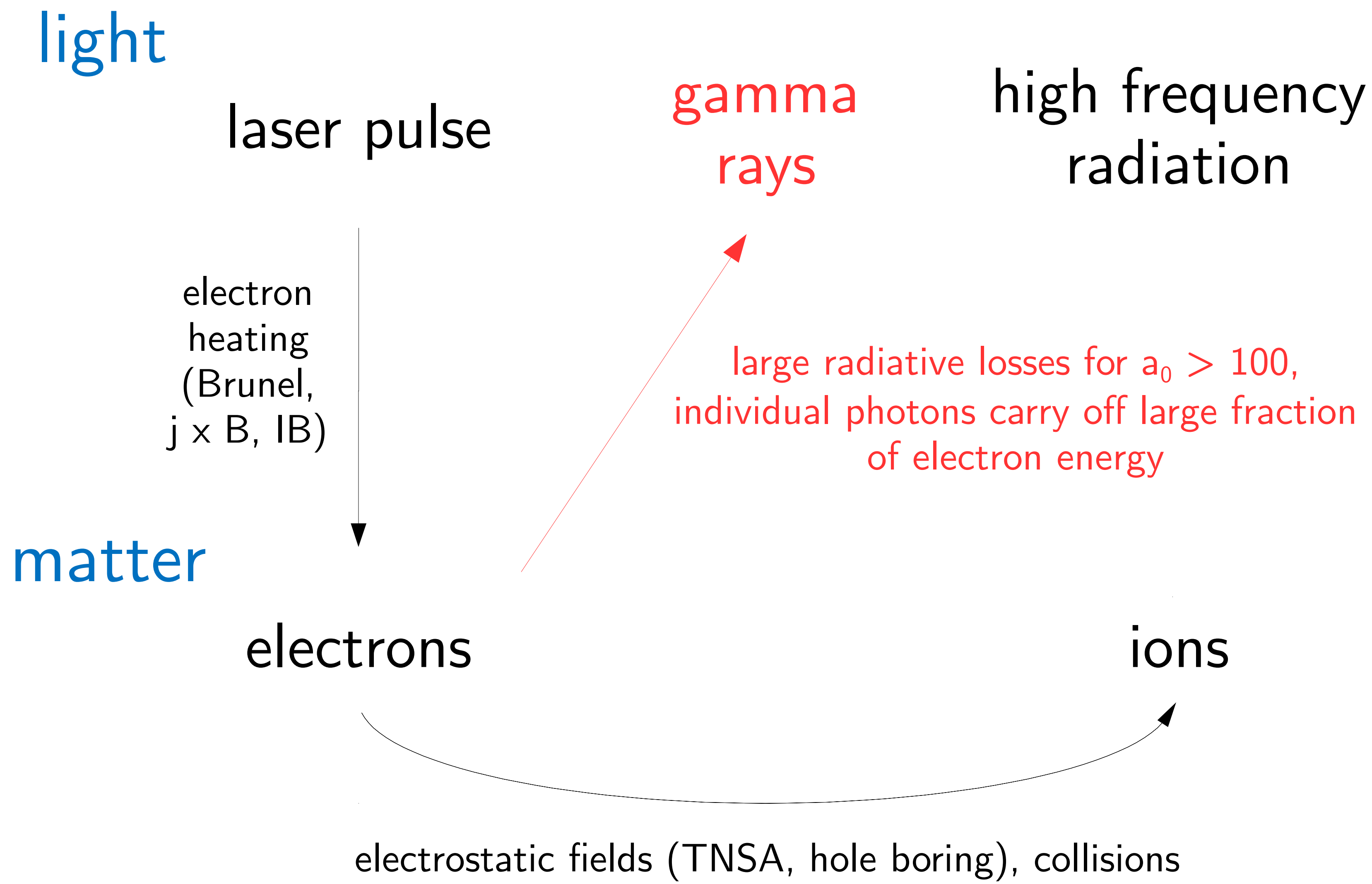
matter

electrons

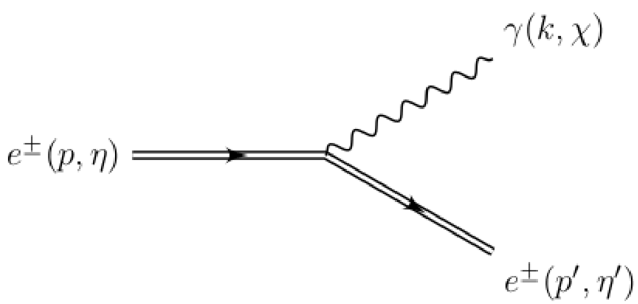
ions

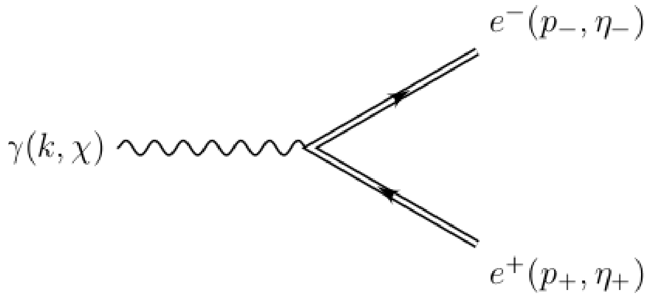
electrostatic fields (TNSA, hole boring), collisions

With gamma ray emission



Electron-positron pair creation

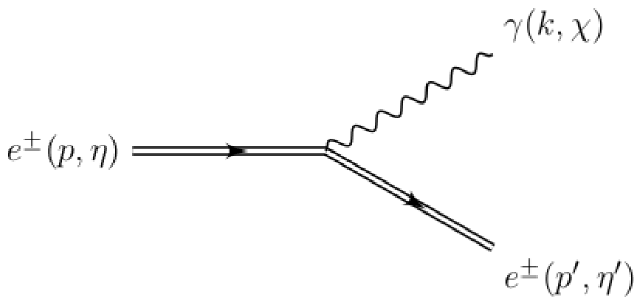


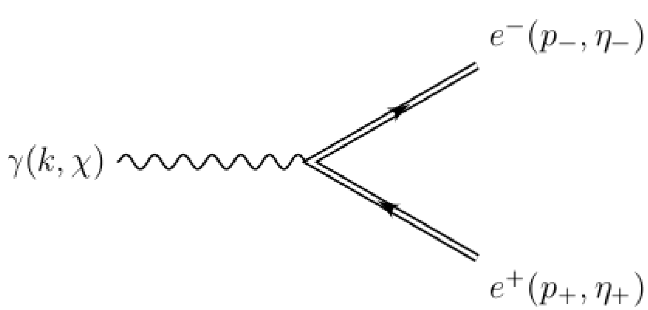


- If we can emit photons with multi-MeV energies, what about pair creation?
- Breit-Wheeler pairs are created when gamma rays collide with photons of the laser pulse.
- Purely quantum phenomenon.

New absorption mechanisms

Electron-positron pair creation



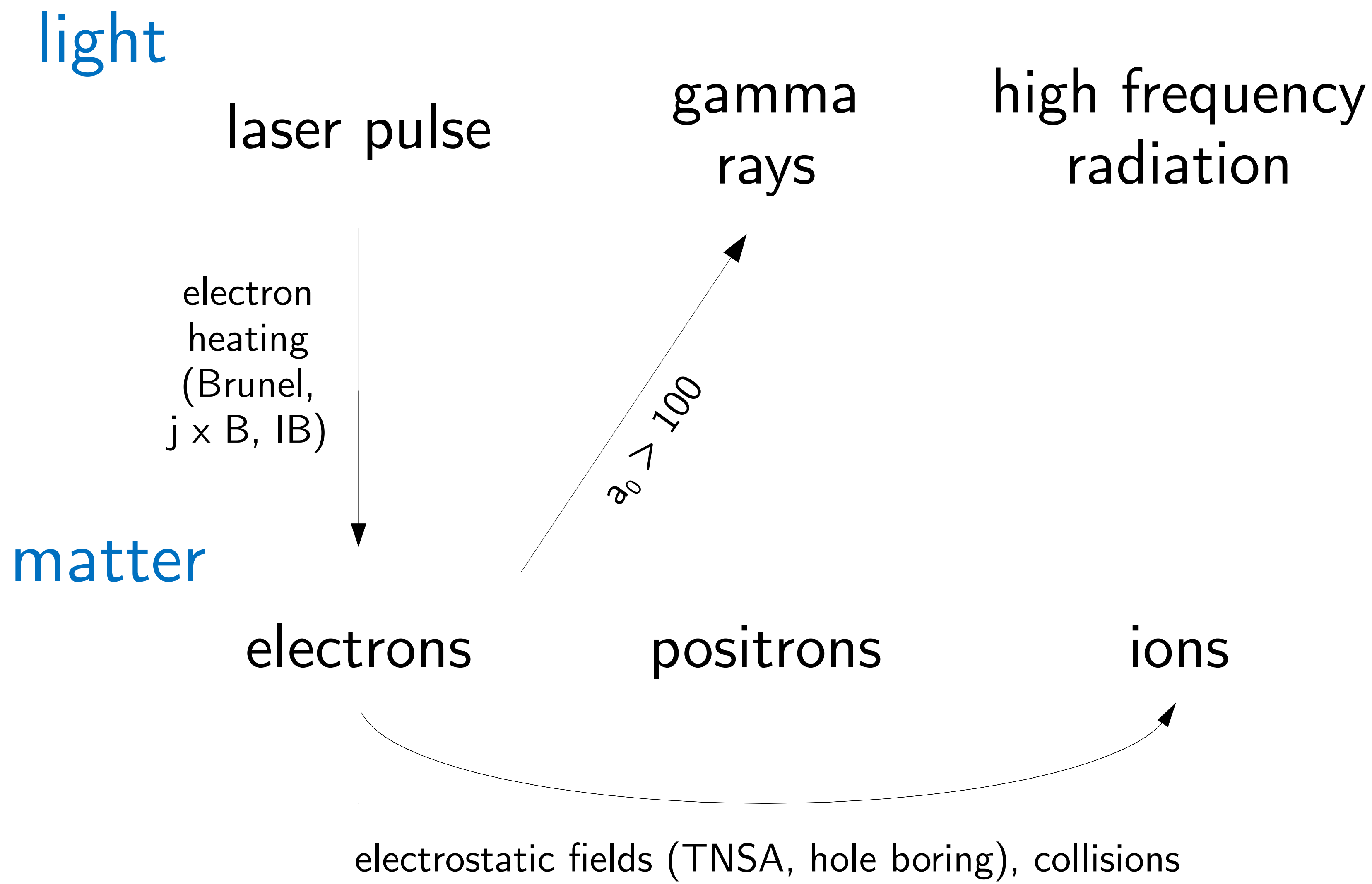


- Pair creation probability depends on the photon χ and the distance over which the intense fields are sustained.
- Result is

$$\frac{d\tau}{dz} \simeq 0.6 \left(\frac{I}{10^{22}\ \mathrm{Wcm}^{-2}} \right)^{1/2} \exp\left(-\frac{4}{3\chi}\right) \mu\mathrm{m}^{-1}$$

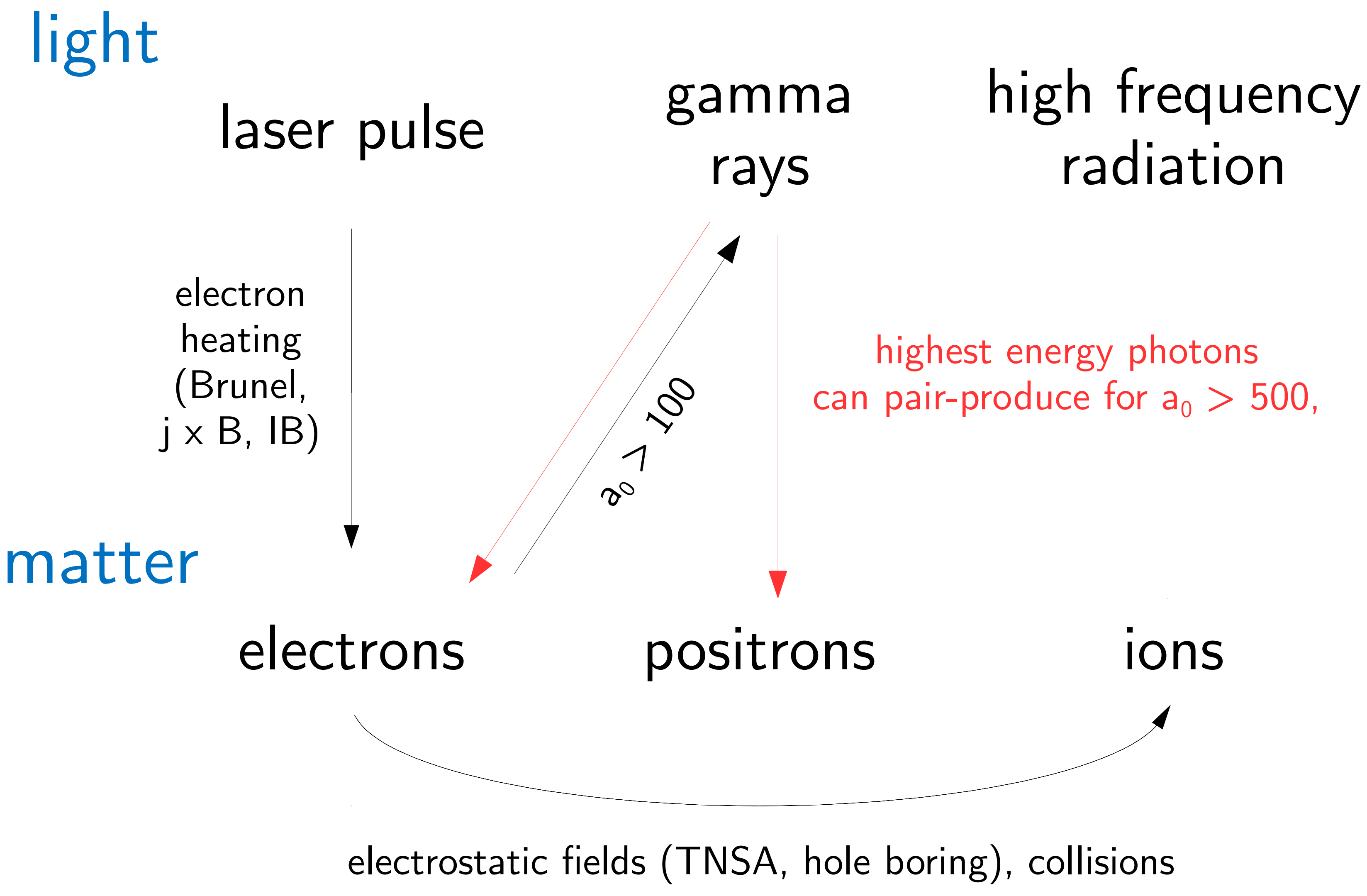
Absorption of laser light

With pair production

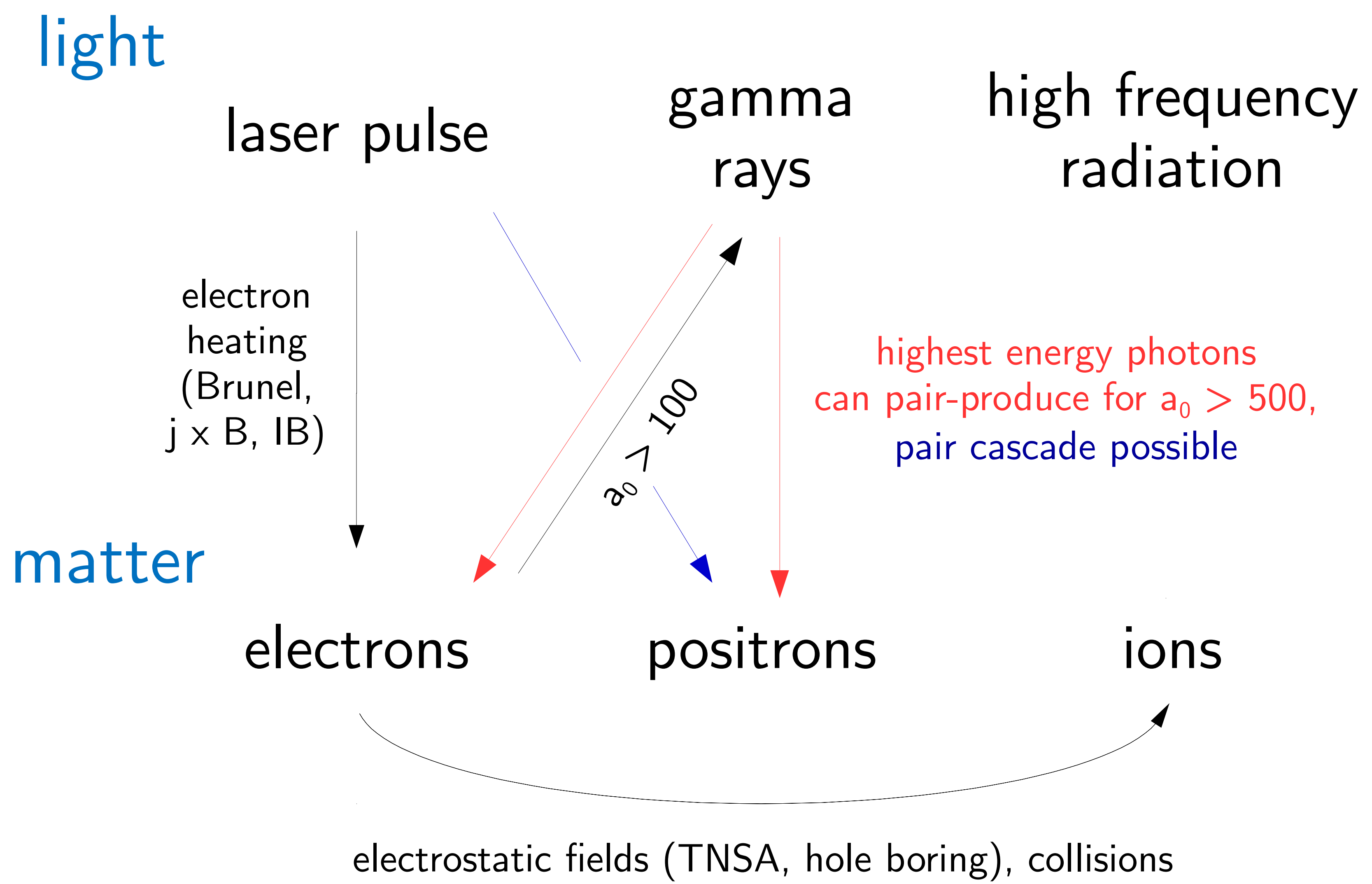


Absorption of laser light

With pair production

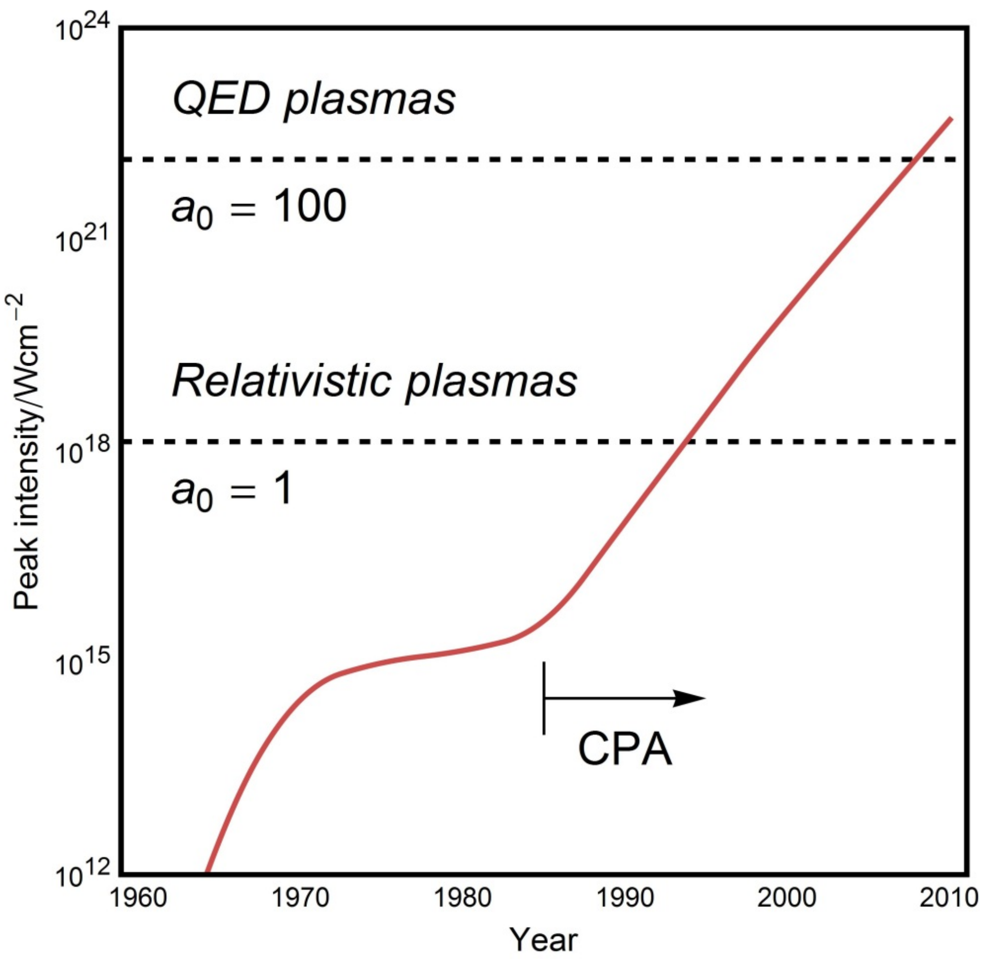


With pair production



Why study QED-plasmas?

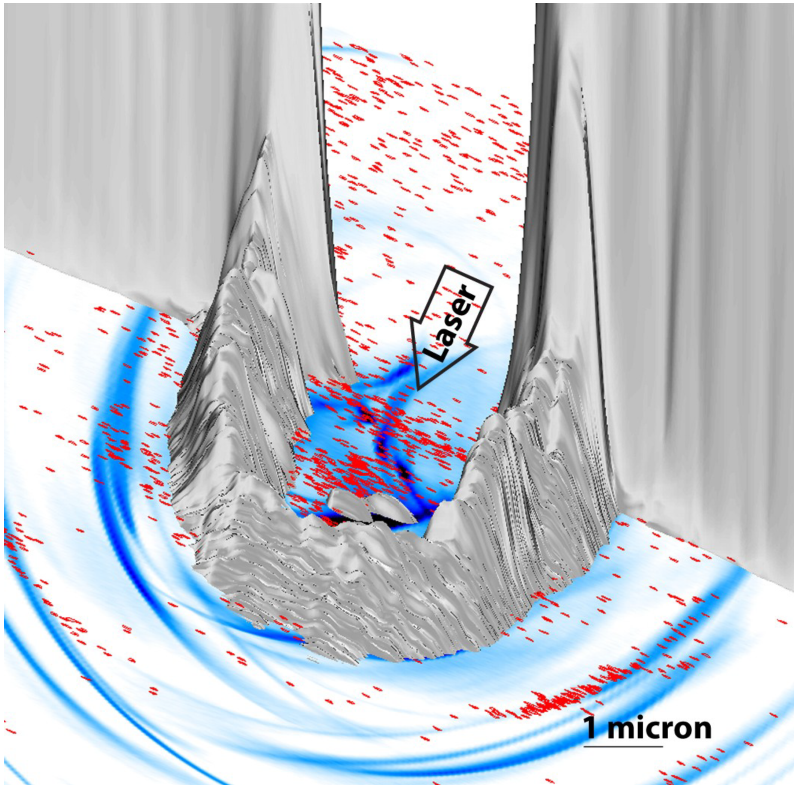
Increasing intensity of short-pulse lasers



- Current intensity record is 2×10^{22} Wcm^{-2} at the HERCULES laser, Michigan.
- Next generation laser facilities (ELI etc.) will exceed 10 PW, 10^{23} Wcm^{-2}.

How can we study QED-plasmas?

Laser-solid interactions at >10 PW



- Important physics across a wide range of timescales.
- 10^{12} particles in the initial state.
- QED processes in a strong background field with complex structure.

Image from C.P. Ridgers et al, PRL 108, 165006 (2012)

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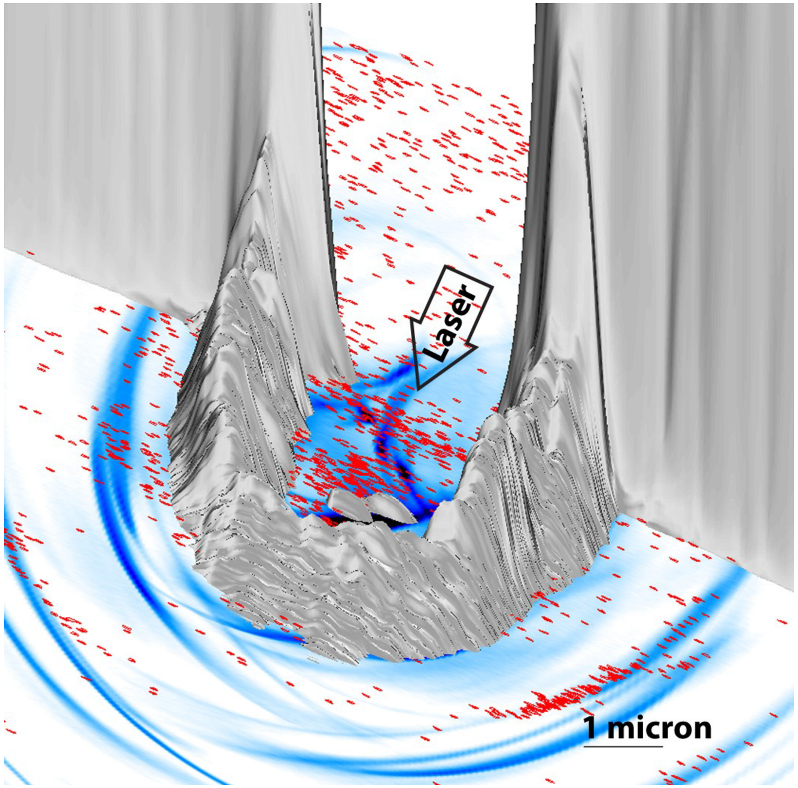
Laser-solid interactions at >10 PW



- Make simplifying assumptions to study these interactions with PIC codes.
- Monte-Carlo modelling of QED events (Duclous et al, PPCF 53, 015009).
- e.g., EPOCH, OSIRIS, PICADOR...

Image from C.P. Ridgers et al, PRL 108, 165006 (2012)

QED-PIC codes

- If the formation length is short enough, we can assume the fields are **quasi-static** over the emission process.

- The formation length is smaller than the laser wavelength by a factor of the strength parameter a_0.

- We also assume the fields are **weak**.

- i.e. the fields invariants *f* and *g* are vanishingly small

$$f = |E^2 - B^2|/E_{\mathrm{crit}}^2$$

$$g = |\boldsymbol{E} \cdot \boldsymbol{B}|/E_{\mathrm{crit}}^2$$

QED-PIC codes

- The rates for photon and pair production can then be calculated in an equivalent system of fields with the same instantaneous value of χ.
- e.g. a static magnetic field in the ultrarelativistic limit: T. Erber, Rev. Mod. Phys. 38, 626 (1966)

- Other constraints on PIC simulations:
- Size of timestep must be set to avoid multiple scatterings (constraint set by rate of photon emission is strongest).
- C. P. Ridgers et al, J. Comp. Phys., 260, 273 (2014)

e.g. laser absorption fraction to gamma-rays

$$
\begin{aligned}
f_e &= \begin{pmatrix} \text{electron} \\ \text{temperature} \\ a_0 mc^2 \end{pmatrix} \times \begin{pmatrix} \text{hot electron} \\ \text{fraction} \\ f_h \end{pmatrix} \times \begin{pmatrix} \text{number} \\ \text{density} \\ a_0 n_{\mathrm{cr}} \end{pmatrix} \Big/ \begin{pmatrix} \text{laser energy} \\ \text{density} \\ \frac{1}{2} a_0^2 mc^2 n_{\mathrm{cr}} \end{pmatrix} \\
&\propto f_h
\end{aligned}
$$

e.g. laser absorption fraction to gamma-rays

$$f_e = \begin{pmatrix} \text{electron} \\ \text{temperature} \\ a_0 mc^2 \end{pmatrix} \times \begin{pmatrix} \text{hot electron} \\ \text{fraction} \\ f_h \end{pmatrix} \times \begin{pmatrix} \text{number} \\ \text{density} \\ a_0 n_{\text{cr}} \end{pmatrix} / \begin{pmatrix} \text{laser energy} \\ \text{density} \\ \frac{1}{2} a_0^2 mc^2 n_{\text{cr}} \end{pmatrix}$$

$$\propto f_h$$

$$f_\gamma = \begin{pmatrix} \text{radiated} \\ \text{energy} \\ \propto \chi^2 g(\chi) \end{pmatrix} \times \begin{pmatrix} \text{hot electron} \\ \text{fraction} \\ f_h \end{pmatrix} \times \begin{pmatrix} \text{number} \\ \text{density} \\ a_0 n_{\text{cr}} \end{pmatrix} / \begin{pmatrix} \text{laser energy} \\ \text{density} \\ \frac{1}{2} a_0^2 mc^2 n_{\text{cr}} \end{pmatrix}$$

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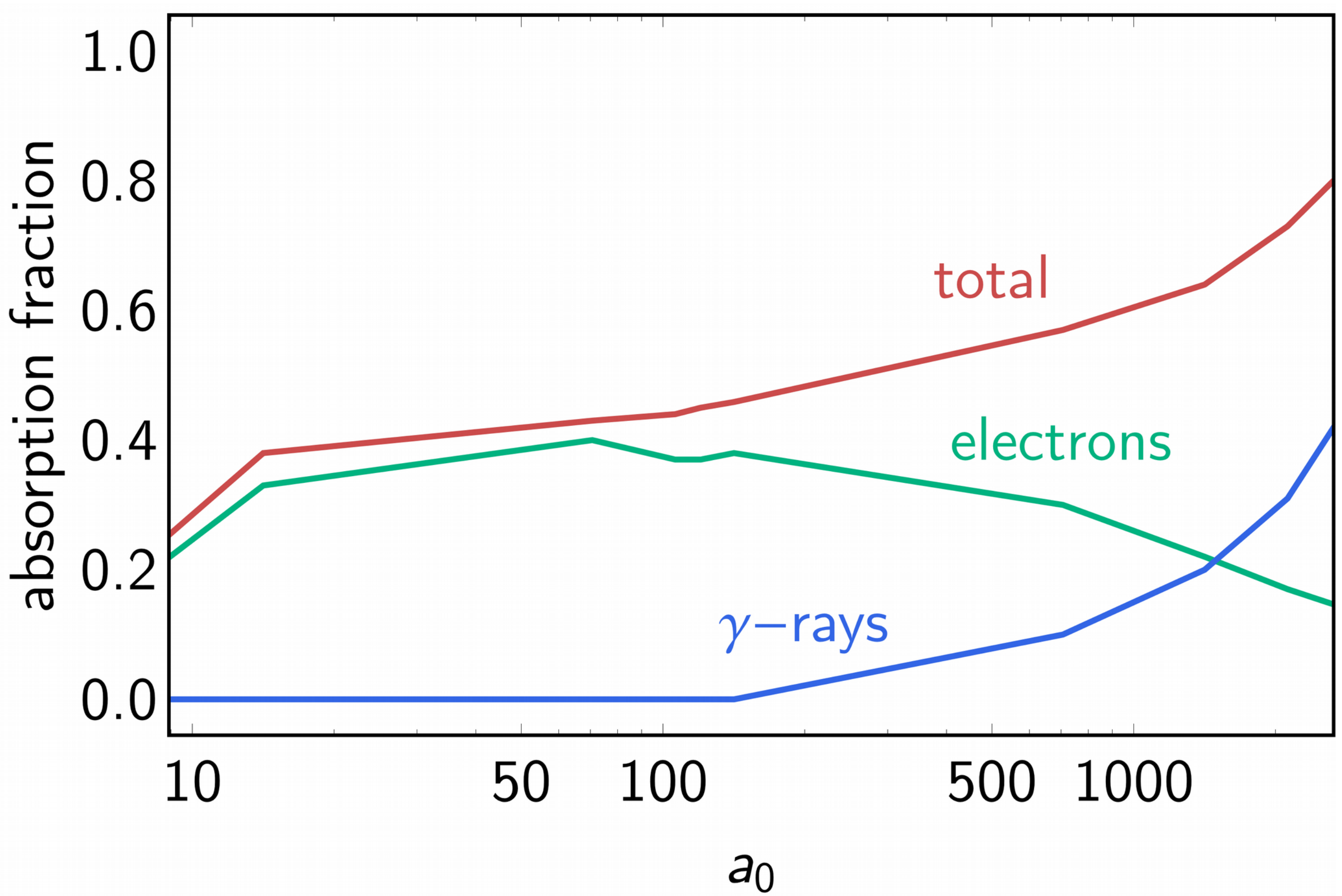
$$\propto f_h \, a_0^3 \, g(\chi)$$

e.g. laser absorption fraction to gamma-rays

2D QED-PIC simulations of 40fs of 1 micron light striking a plasma with density just above critical:



e.g. laser absorption fraction to gamma-rays

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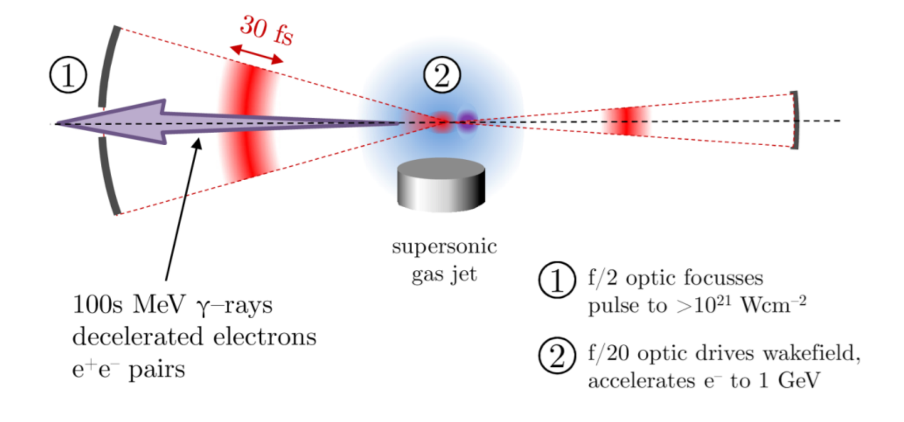
$$\propto f_h\, a_0^3\, g(\chi)$$

When a_0 is high enough that a substantial fraction of the laser energy is absorbed to gamma rays, we also have $\chi > 0.1$.

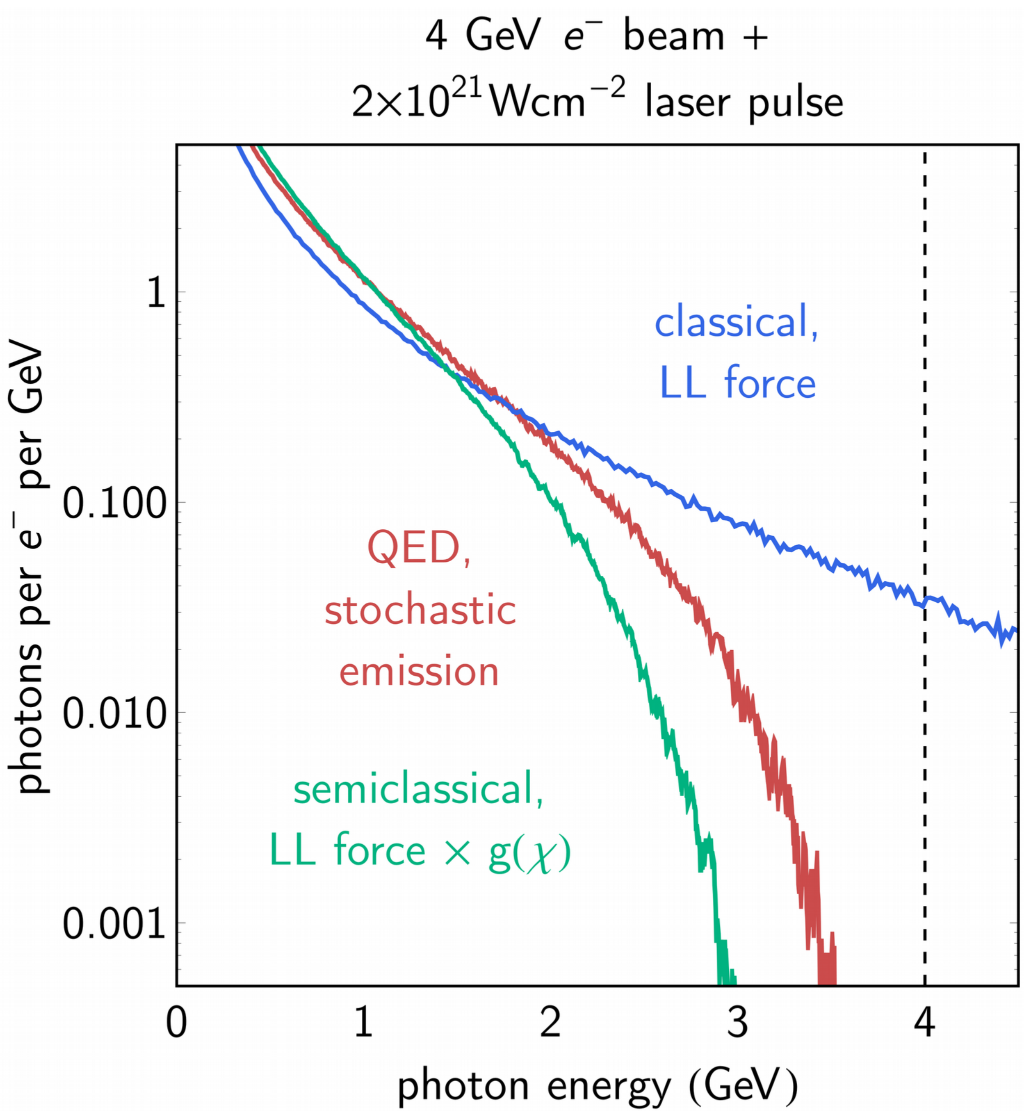
Colliding intense laser and multi-GeV electrons



- $\chi = \gamma\, E \,/\, E_{Sch}$
- Accelerate electrons to high energies before they encounter a high intensity field.
- Use gamma ray spectra to distinguish quantum from classical radiation reaction.

What is possible with today's PW lasers?

Colliding intense laser and multi-GeV electrons



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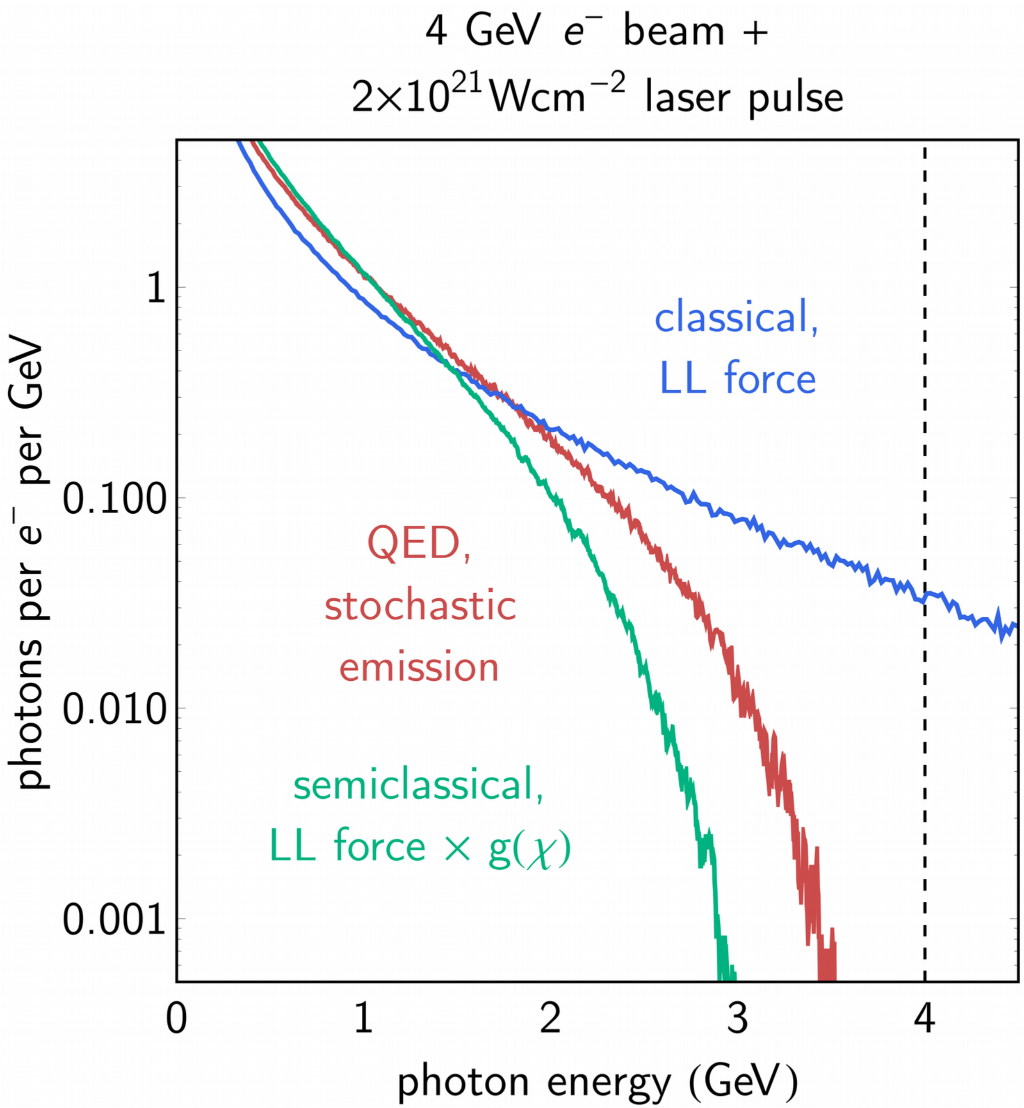
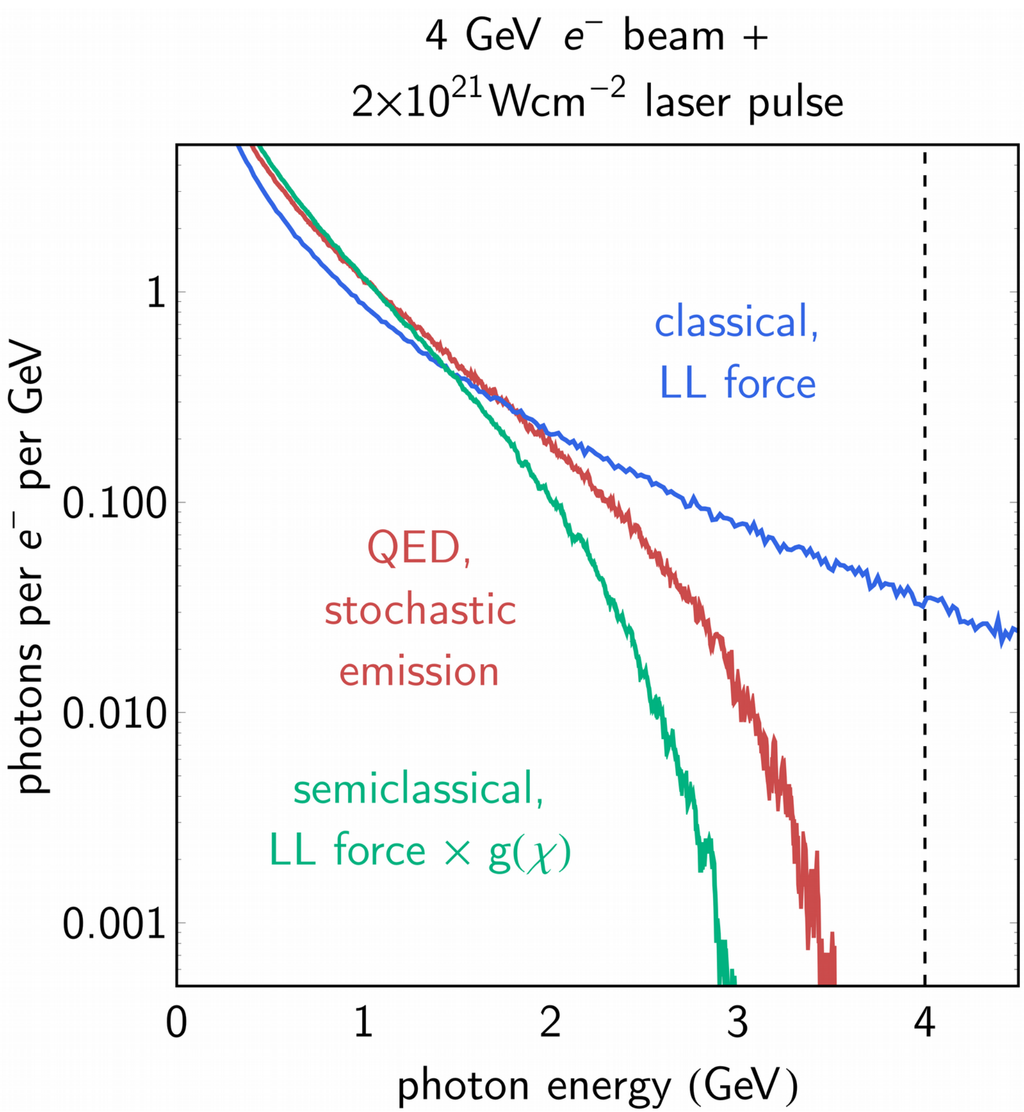


- "Photon energy" in classical emission is unbounded, overestimates high-energy tail (a lot).
- Correcting the radiated intensity by g(χ), but without treating emission probabilistically, underpredicts that tail.

What is possible with today's PW lasers?

Colliding intense laser and multi-GeV electrons



- Reproducibility of electron beam – given the initial energy and the photon spectra, determine a_0 of target laser consistent with either classical and quantum emission.
- Only one of these will be consistent with the actual laser pulse.

- Next generation laser facilities will produce plasmas dominated by radiation reaction and QED processes.

- We can begin to study these interactions using QED-PIC simulations.

- But we can (and need to) to validate the model used in those simulations with colliding-beam experiments possible with the BELLA facility.